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Effects of temperature and stress on the interface between concrete and its carbon fiber epoxy-matrix composite retrofit, studied by electrical resistance measurement

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Abstract

DC electrical resistance measurement was used to investigate the effects of temperature and stress on the interface between a concrete substrate and its carbon fiber epoxy-matrix composite retrofit. The apparent resistance of the retrofit in the fiber direction was increased by bond degradation, whether the degradation was due to heat or stress. The degradation was reversible. Irreversible disturbance in the fiber arrangement occurred slightly as thermal or load cycling occurred, as indicated by the resistance decreasing cycle by cycle. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Concrete; Electrical properties; Cycles; Retrofit; Composite

1. Introduction

Continuous fiber polymer-matrix composites are increasingly used to retrofit concrete structures, particularly columns [1–13]. The retrofit involves wrapping a fiber sheet around a concrete column or placing a sheet on the surface of a concrete structure, such that the fiber sheet is adhered to the underlying concrete using a polymer, most commonly epoxy. This method is effective for the repair of even quite badly damaged concrete structures. Although the fibers and polymer are very expensive compared to concrete, the alternative of tearing down and rebuilding the concrete structure is often even more expensive than the composite retrofit. Both glass fibers and carbon fibers are used for the composite retrofit. Glass fibers are advantageous for their relatively low cost, but carbon fibers are advantageous for their high tensile modulus.

The effectiveness of a composite retrofit depends on the quality of the bond between the composite and the underlying concrete, as good bonding is necessary for load transfer. Peel testing for bond quality evaluation is destructive [14]. Nondestructive methods to evaluate the bond quality are valuable. They include acoustic methods, which are not sensitive to small amounts of debonding or bond degradation [15], and dynamic mechanical testing [16]. This paper uses electrical resistance measurement for nondestructive evaluation of the interface between concrete and its carbon fiber composite retrofit. The method was found to be effective for studying the effects of temperature and debonding stress on the interface. The concept behind the method is that bond degradation causes the electrical contact between the carbon fiber composite retrofit and the underlying concrete to degrade. Since concrete is electrically more conducting than air, the presence of an air pocket at the interface causes the measured apparent volume resistance of the composite retrofit in a direction in the plane of the interface to increase. Hence, bond degradation is accompanied by an increase in the apparent resistance of the composite retrofit. Although the polymer matrix (epoxy) is electrically insulating, the presence of a thin layer of epoxy at the interface was found to be unable to electrically isolate the composite retrofit from the underlying concrete.

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2. Experimental methods

For the concrete, the cement used was Portland cement (Type I) from Lafarge (Southfield, MI); the fine aggregate used was natural sand (all passing #8 US sieve, 99.9% SiO_2); the coarse aggregate used was natural gravel (all passing #4 US sieve); the cement/sand/gravel ratio was 1:1.5:2. The water/cement ratio was 0.5. A water-reducing agent (TAMOL SN, Rohm and Hass, Philadelphia, PA; sodium salt of a condensed naphthalenesulphonic acid) was used in the amount 2% of the cement weight.

To prepare the concrete, mixing was carried out by (i) mixing cement, sand, and water in a rotary mixer with a flat beater, (ii) adding the water-reducing agent, (iii) stirring with the rotary mixer for $\sim$ 5 min, (iv) pouring into a stone concrete mixer, (v) adding gravel and mixing for $\sim$ 3 min, and (vi) pouring into oiled molds. After pouring into molds, an external vibrator was used to facilitate compaction and to decrease the amount of air bubbles. The samples were demolded after 24 h and then cured in a moist room (relative humidity = 100%) for 28 days. The surfaces of cured concrete blocks (51.5 $\times$ 51.0 $\times$ 50.0 mm) were mechanically polished by using 600-grit sandpaper, in which the average SiC abrasive particle size was 25 μm.

The carbon fiber sheet used was MRK-M2-20 from Mitsubishi Chemical (Japan). Table 1 describes its properties. The epoxy resin used was LOT 7293-1 from Dexter (Pittsburg, CA). A 40 $\times$ 15 mm sample of carbon fiber sheet, with the fibers along the 40 mm length of the sample, was pressed against a surface of the polished concrete block while the epoxy resin was at the interface for the purpose of bonding the fiber sheet to the concrete, as illustrated in Fig. 1. The curing of the epoxy resin was carried out at room temperature for 120 h.

Four electrical contacts (A, B, C and D) were applied at four points along the 40 mm length of the fiber sheet sample, such that each contact was a strip stretching across the 15 mm width of the sample (Fig. 1). Each electrical contact was in the form of silver paint in conjunction with copper wire. In the four-probe method used for DC electrical resistance measurement, two of the electrical contacts (A and D, Fig. 1) were for passing current; the remaining two contacts (B and C) were for measuring voltage. The voltage divided by the current gave the measured resistance, which was the apparent volume resistance of the fiber sheet between B and C when the sheet was in contact with the concrete substrate. A Keithley 2001 multimeter was used.

Table 1
Properties of the carbon fiber sheet

Product number	Fiber area weight (g/mm^2)	Thickness (mm)	Tensile strength (MPa)	Tensile modulus (GPa)
MRK-M2-20	200	0.111	3400	230

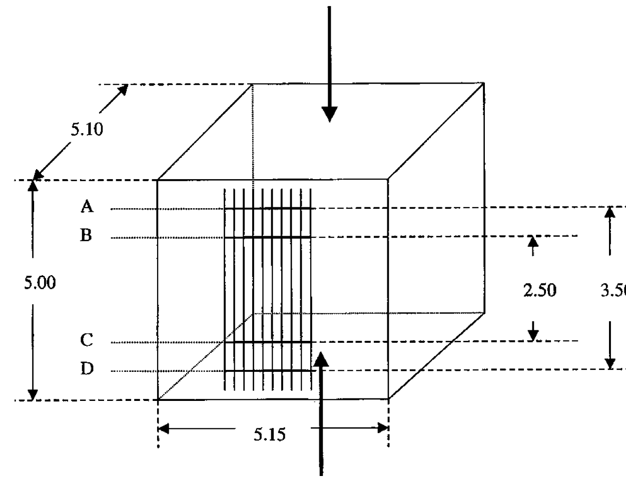

Fig. 1. Sample configuration. The arrow direction is the direction of compressive loading. All dimensions are in cm. A, B, C and D are the four electrical leads (dotted lines) emanating from the four electrical contacts (thick lines), which are attached to the fiber retrofit indicated by vertical parallel lines on the front face of the concrete block. The fiber direction is in the stress direction.

In order to investigate the interface between epoxy and carbon fiber within the fiber sheet, fiber sheet samples without a concrete substrate were made by pressing the sheet against a PTFE film (instead of concrete), while epoxy resin was at the interface. After curing, the PTFE film was peeled off. Electrical resistance was measured in the fiber direction of the fiber sheet, as described above for the case of having a concrete substrate.

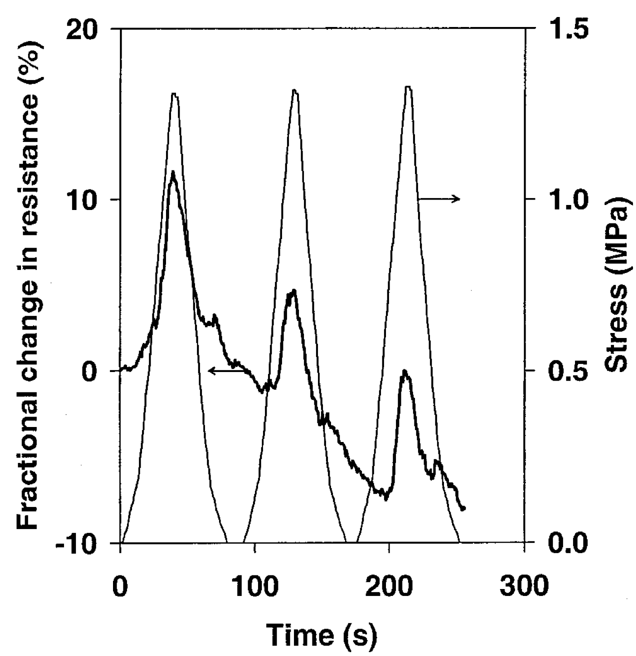

Fig. 2. The fractional change in resistance for the fiber retrofit on a concrete substrate during cyclic compressive loading.

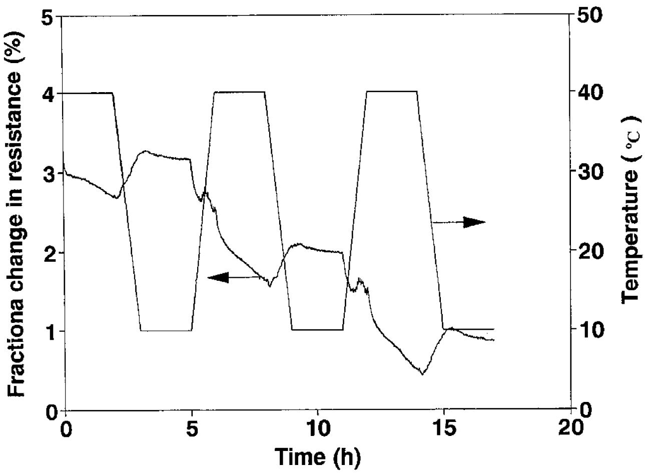

Fig. 3. The fractional change in resistance for the carbon fiber epoxy-matrix composite (without a substrate) during thermal cycling.

Thermal cycling was conducted by (i) holding at 40°C for 2 h, (ii) cooling from 40°C to 10°C at a cooling rate of 0.5°C/min, (iii) holding at 10°C for 2 h, (iv) heating from 10°C to 40°C at a heating rate of 0.5°C/min, and (v) repeating steps (i)–(iv) for three times in order to have three thermal cycles. During the temperature variation, the electrical resistance was continuously measured.

Uniaxial compression was applied on a concrete block with fiber sheet on one surface, such that the stress was in the fiber direction (Fig. 1), using a screw-action mechanical testing system (Sintech 2/D, Sintech, Research Triangle Park, NC), while the electrical resistance was continuously measured.

3. Results and discussion

3.1. Effect of stress on the interface

Fig. 2 shows the fractional change in resistance during cyclic compressive loading at a stress amplitude of 1.3 MPa. The stress was along the fiber direction. Stress returned to zero at the end of each cycle. In each cycle, the electrical resistance increased reversibly during compressive loading. This is attributed to the reversible degradation of the bond between carbon fiber sheet and concrete substrate during compressive loading. This bond degradation decreased the chance for fibers to touch the concrete substrate, thereby leading to a resistance increase.

As cycling progressed, both the maximum and minimum values of the fractional change in resistance in a cycle decreased. This is attributed to the irreversible disturbance in the fiber arrangement during repeated loading and unloading. This disturbance increased the chance for fibers to touch the concrete substrate, thereby causing the resistance to decrease irreversibly as cycling progressed.

As shown in Fig. 2, the first cycle exhibited the highest value of the fractional change in resistance. This is due to the greatest extent of bond degradation taking place during the first cycle.

3.2. Effect of temperature on the interface

Fig. 3 shows the fractional change in resistance for the carbon fiber epoxy-matrix composite (without a substrate) during thermal cycling in which the temperature range was from 10°C to 40°C. The resistance increased reversibly upon cooling. This is attributed to thermal stress. Upon cooling, thermal stress build-up caused the fiber arrangement to be disturbed, thereby resulting in a resistance increase. In the part of each thermal cycle in which the temperature was kept at 40°C, the resistance decreased slightly. This is probably due to post-curing occurring at 40°C. The post-curing caused the fiber to be closer to one another, thereby causing the resistance to decrease. The range of fractional change of resistance for each cycle was less than 2%.

Fig. 4 shows the fractional change in resistance for the fiber retrofit with a concrete substrate during thermal cycling in which the temperature range was from 10°C to 40°C. The resistance increased reversibly upon heating. This is opposite to the trend in Fig. 3. Upon heating, the mismatch of the coefficient of thermal expansion between composite retrofit and concrete substrate probably led to bond degradation and consequent increase in resistance. As cycling progressed, both the maximum and minimum values of the fractional change in resistance decreased, as in Fig. 2. This is attributed to the irreversible disturbance in the fiber arrangement and the consequent increase in the chance for fibers to contact the concrete substrate. The range of fractional change in resistance within each cycle was more than 50% in Fig. 4 (much larger than the 2% range in Fig. 3). This means that the thermal stress within the composite

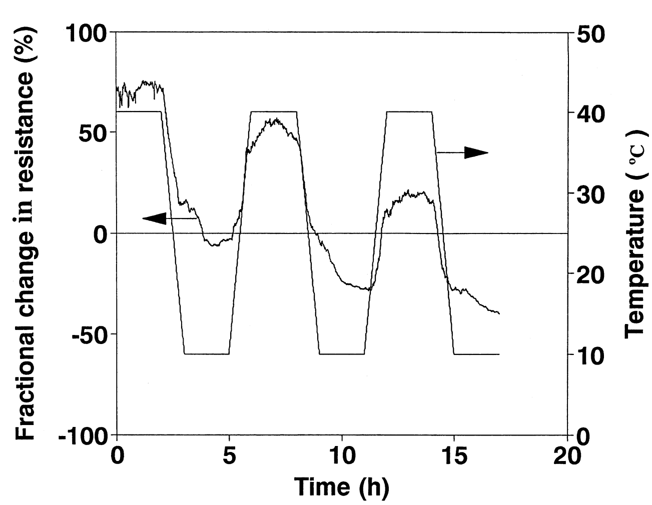

Fig. 4. The fractional change in resistance for the fiber retrofit on a concrete substrate during thermal cycling.

(Fig. 3) had much less effect on the measured resistance than bond degradation (Fig. 4).

4. Conclusion

The DC electrical resistance measurement was used to study the effects of temperature and stress on the interface between concrete and its carbon fiber epoxy-matrix composite retrofit. Both heating and mechanical loading caused bond degradation, which was reversible. The apparent electrical resistance of the retrofit in the fiber direction was increased by bond degradation. It reversibly increased during compressive loading of the concrete in the fiber direction and during heating. The bond degradation decreased the chance for fibers to touch the concrete substrate, thereby causing the resistance to increase. As thermal or mechanical cycling progressed, the resistance decreased from cycle to cycle, due to disturbance in the fiber arrangement and the consequent increase in the chance for fibers to touch the concrete substrate.

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